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The Seismic Performance in Diaphragm Plane of Multi-Storey Timber and Concrete Hybrid Structure

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Abstract

The timber and concrete hybrid structure is constructed by concrete frame and light frame wood diaphragm and roof system, which is suitable for multi-storey buildings. In this paper, based on the deformation characteristic of wood diaphragm under lateral load, diagonal elastic springs were used to simulate the in-plane stiffness of wood diaphragm in order to simplify the structural modeling. Sap2000 was used to set up three different numerical structural models for a 6-storey hybrid building, including simplified wood diaphragm model, rigid floor model and flexible floor model. These models were analyzed with response spectrum model analysis method under frequent earthquake and time history method under rare earthquake. At last, two design plans for a 6-storey building, one with wood diaphragm, the other with concrete floor, were compared. Results showed that, the lateral forces and the displacement of the concrete frame with the wood diaphragm model lay between rigid floor model and flexible model; using wood diaphragm could maximally lower down the load of seismic and the foundation cost.

Keywords: Concrete structure, Wood diaphragm, Hybrid structure, Seismic analysis, Sap2000

1. INTRODUCTION

Wood is a renewable and environmental friendly building material, and timber structures, which have many advantages such as fast construction and good performance in earthquake, are very popular in developed countries, such as North European countries, USA, Canada and Japan. In last ten years, light

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frame wood buildings came into China's market and made certain approaches. However, traditional light fame timber houses are low density residential buildings, which are not accordant with the situation of China with limited land but a large population (He and Lam 2004).

In this background, a type of hybrid structure, combined of concrete frames and wood diaphragms, is raised. In this hybrid structure, reinforced concrete is used to build up frames, providing resistance for horizontal and lateral load, while wood diaphragms are used as floor system. This kind of structure could be applied in multi-storey buildings, which saves more land than traditional timber structure. Due to the lightness of the wood diaphragm, the dead load and lateral seismic load are maximally reduced. At the same time, because wood is an environmental friendly building material, this kind of hybrid structure could lower down the carbon emission of building material. However, how the wood diaphragm and concrete frames working together under lateral load should be further studied. Since research in this area is very limited, the studies on the structural model of light frame timber structure could be referred to (Chehab 1982; Kasal et al. 1994; Ceccoti et al. 2000; Folz et al. 2001).

2. SIMPLIFIED WOOD DIAPHRAGM

For a real large hybrid structure, it is very time-consuming and complex to set up structural models which include all the structural elements. In order to solve this problem, a simplified wood diaphragm model is brought up, replacing the wood diaphragm with diagonal elastic springs. First, calculate the stiffness of the diaphragm k_d , then calculate the stiffness of the diagonal springs k_s , as in Figure 2.

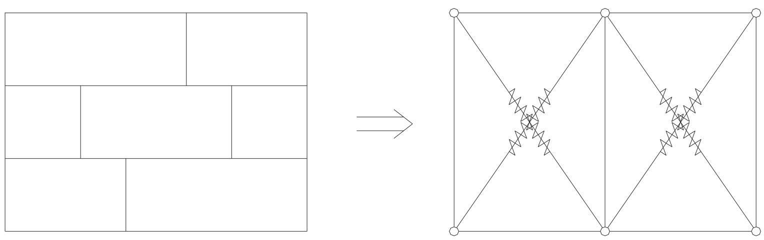


Figure 1: Simplified wood diaphragm model.

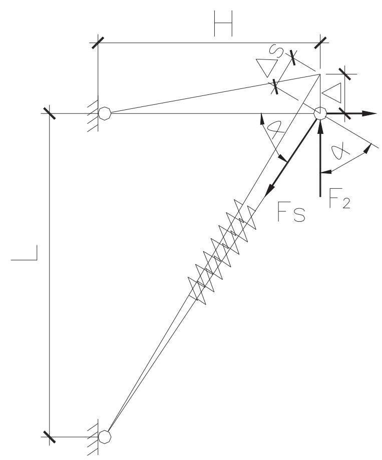


Figure 2: Calculation of the spring's stiffness.

$$k_s = \frac{k_d}{2} \times \frac{L^2 + H^2}{L^2} \tag{1}$$

3. SEISMIC ANALYSIS OF A SIX-STOREY HYBRID STRCUTRE

There are two different assumptions considering floor's in-plane stiffness in structural analysis under lateral load, rigid floor assumption and flexible floor assumption. For rigid floor assumption, the floor is a rigid panel, and lateral forces are distributed by the stiffness of lateral resistance elements. For flexible floor assumption, the floor's in-plane stiffness is zero, the lateral force distribution is based on how much vertical loads the lateral force resist elements take. In this part, a six-storey hybrid structural model with simplified wood diaphragm is analyzed under seismic load and the results are compared with rigid floor model and flexible floor model.

3.1. Project introduction

The project is a 6-storey building which floor height is 3 m, constructed by concrete frame and wood diaphragm, the structural plan view is Figure 3. The earthquake design group is 2, seismic fortification intensity is 7, basic design acceleration of ground motion is 0.1g, site classification is Ⅱ, and the design anti-seismic grade is grade 3, characteristic period of ground motion is 0.40 s, seismic influence coefficient is 0.08. Concrete grade is C30, longitudinal bar is HRB400, and stirrup is HPB235. The bar arrangement of beams and columns are showed in Figure 4.

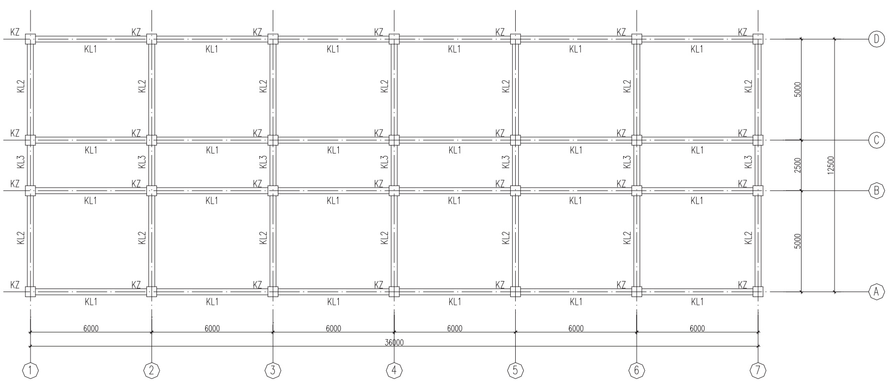
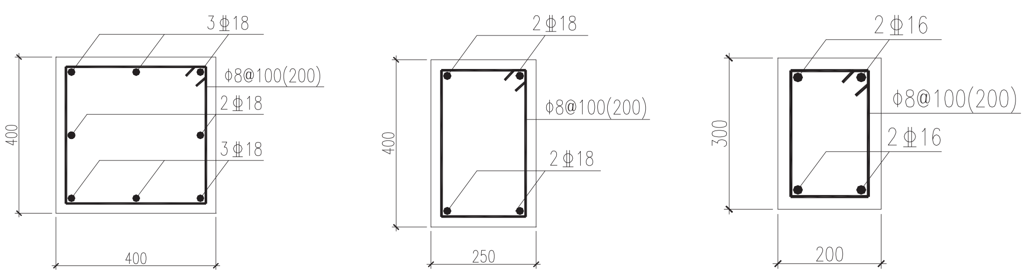


Figure 3: Plan view of the structure



(a) KZ1 (b) KL1, KL2 (c) KL3

Figure 4: Bar arrangement drawings

Characteristic value of uniformly distributed dead load is 1.0 kN/m^2, and live load is 2.0 kN/m^2. There are two different sizes of wood diaphragms: 5m×6m and 2.5m×6m. The wood joists are chosen by the span, spacing and load. 15.5 mm thick OSB are used as sheathing panel. The sheathing-to-frame nail is 51mm long, with diameter 2.85mm. Rim nail spacing is 150mm and inner nail spacing is 300mm. Based on the construction detail of the diaphragm, formula 1 are used to calculate the stiffness of the diagonal springs k_s in the simplified wood diaphragm model. Sap2000 is used to set up the structural model. When k_s =0, the model is changed to flexible floor model. When $k_s = \infty$, the rigid floor model is obtained.

3.2. Frequently occurred earthquake analysis

Model analysis method is used for the structural analysis under frequently occurred earthquake. The calculation results are shown in Table 1~ Table 3.

Table 1: Storey displacement and inner story drift

Floor	Storey displacement（mm）			Inner storey drift		
	Wood diaphragm	Rigid floor	Flexible floor	Wood diaphragm	Rigid floor	Flexible floor
1	2.62	2.51	2.86	1/1145	1/1195	1/1049
2	6.94	6.62	7.56	1/694	1/730	1/638
3	11.09	10.61	12.10	1/723	1/752	1/661
4	14.53	13.91	15.85	1/872	1/909	1/800
5	17.00	16.27	18.55	1/1215	1/1271	1/1111
6	18.43	17.64	20.11	1/2098	1/2190	1/1923

Table 2: Lateral seismic force in each frame Unit: kN

Frame axis	1	2	3	4	Total lateral force
Wood diaphragm	94.10	101.04	105.48	107.00	708.24
Rigid floor	102.22	102.22	102.22	102.22	715.54
Flexible floor	79.98	98.08	111.92	117.08	697.04

Table 3: Displacement on the top of each frame Unit: mm

Frame axis	1	2	3	4
Wood diaphragm	16.54	17.54	18.02	18.43
Rigid floor	17.63	17.63	17.63	17.63
Flexible floor	14.22	17.09	19.29	20.11

The results show that, all of the three models could meet the requirement of limited elastic storey drift in code. The total seismic forces of three models are pretty close, but the distribution is different: in the rigid floor model, each frame takes the same force; in the wood diaphragm model and flexible floor model, the mid-frame take higher force that the side-frame. The displacement results reflect the same pattern.

3.3. Rarely occurred earthquake analysis

Time history method is used to do the rarely occurred earthquake analysis. ElCentro earthquake record is selected as the earthquake wave. The plastic hinges are defined at the ends of beams and columns. The results are showed in Table 4~Table 6.

Table 4: Storey displacement and inner storey drift

Floor	Level displacement（mm）			Story drift		
	Wood diaphragm	Rigid floor	Flexible floor	Wood diaphragm	Rigid floor	Flexible floor
1	6.81	6.79	7.46	1/441	1/442	1/402
2	21.25	21.1	23.63	1/208	1/210	1/186
3	36.89	36.23	41.57	1/192	1/198	1/167
4	49.2	47.58	56.05	1/244	1/264	1/207
5	56.61	54.5	64.84	1/405	1/434	1/341
6	60.05	57.5	69.03	1/872	1/1000	1/716

Table 5: Distribution of lateral seismic force Unit: kN

Frame axis	1	2	3	4	Total lateral force
Wood diaphragm	142.58	153.14	154.94	156.50	1061.18
Rigid floor	153.20	153.20	153.20	153.20	1072.40
Flexible floor	132.56	152.14	153.68	153.80	1030.56

Table 6: Displacement on the top of each frame Unit: mm

Frame axis	1	2	3	4
Wood diaphragm	57.58	58.88	59.79	60.05
Rigid floor	57.49	57.49	57.49	57.49
Flexible floor	46.55	54.70	64.62	69.03

The results show that, all of the three models could meet the requirement of limited plastic storey drift in the code. The total seismic forces of three models are pretty close. The force distribution and displacement are following the same pattern with the frequently occurred earthquake analysis.

Figure 5 is the time-displacement curve on the top of mid-frame in three models. The wood diaphragm model's curve is quite close with rigid model's curve. The flexible floor model's curve follows the same pattern but amplitude is bigger.

4. COMPARISON BETWEEN WOOD DIAPHRAGM AND CONCRETE FLOOR

Wood diaphragm is much lighter than concrete floor, so it could maximally lower down the seismic force and the load on the foundation. In this part, a 6-storey building designed with two different floor system, wood diaphragm and concrete floor. The design conditions of the project are same with the one in Part 3. Two designs are compared in structural weight, lateral seismic force, load on the foundation and the cross section of concrete columns. Results are showed in Table 7.

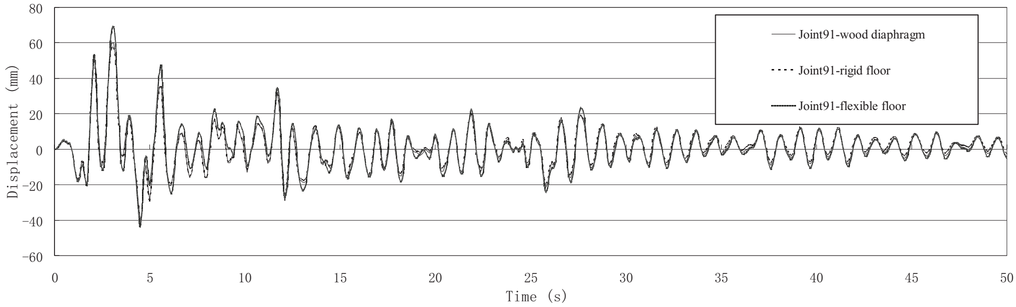


Figure 5: Time-displacement curve of three models

Table 7: Comparisons of Two designs Unit: mm

	Wood diaphragm	Concrete floor	Wood/Concrete
Structural weight (kN)	8120	16172	50%
Lateral seismic force (kN)	728	1324	55%
Load on the foundation (kN)	16636	26288	63%
Cross section of concrete column on the 1st floor (mm)	400x400	500x500	64%

Compared to the design with concrete floor, wood diaphragm plan reduces the structural weight by 50%, the lateral seismic force by 45%, and the load on the foundation by 37%. So, it is very significant to use wood diaphragm to cut down the seismic force and foundation cost. At the same time, the section dimensions are much smaller in the design with wood diaphragm than with concrete floor, which could save the usable floor space.

5. CONCLUSIONS

This paper presented a type of timber and concrete hybrid structure, brought up the simplified wood diaphragm model, and did seismic analysis for a six-storey hybrid structure with three different floor models, the wood diaphragm model, the rigid floor model and the flexible model. At last, two designs for a 6-storey building, one with wood diaphragm, the other with concrete floor, were compared. Results showed that, the lateral forces and the displacement of the concrete frame with the wood diaphragm model lay between rigid floor model and flexible model; using wood diaphragm could maximally lower down the seismic load and foundation cost.

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